Application of Self-Organizing Systems in Power Systems Control

Sven C. Müller[1], Ulf Häger[1], Christian Rehtanz[1], and Horst F. Wedde[2]

[1] Institute of Energy Systems, Energy Efficiency and Energy Economics,
TU Dortmund University of Technology, Dortmund, Germany
`{svenchristian.mueller,ulf.haeger,`
`christian.rehtanz}@tu-dortmund.de`
[2] Chair of Operating Systems and Computer Architecture,
TU Dortmund University of Technology, Dortmund, Germany
`horst.wedde@udo.edu`

Abstract. The European electrical transmission network is operated increasingly close to its operational limits due to market integration and increased feed-in by renewable energies. For this reason, innovative solutions for a reliable, secure and efficient network operation are requested. The application of self-organizing systems promises significant potential in real-time control. This paper outlines the challenges of power system operation, gives a brief overview of relevant system characteristics and discusses the applicability of self-organizing systems for different fields of power system control. As a result of current research, the application of an agent-based decentralized power flow control system is presented and discussed in comparison to current practice based on central decision making.

Keywords: Self-organizing systems, power system control, smart grids, multi-agent systems, power flow control, FACTS.

1 Introduction and Scope

Large-scale power systems like the European electrical transmission system constitute safety-critical physical systems of a high degree of complexity. The electrical transmission network allows for the synchronous operation on alternating current (AC) of almost all parts of continental Europe and forms an interconnected system supplying millions of loads by several hundred conventional power plants as well as more than a million distributed generation units based on renewable energy sources. Due to the liberalization of the European electricity market and feed-in from renewable energies the transmission network has to adapt to a higher base loading and increasing volatility of power flows. It is becoming more and more important to develop innovative solutions to operate the system reliably and securely close to its operational limits in real-time.

The network operation is managed by Transmission System Operators (TSOs) which have to ensure reliability, security and efficiency [1]. Typically there is one

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national TSO being state-owned or regulated by a national regulatory authority. Much of operation related decision making is undertaken centrally by the TSOs or is out of its controllability in the current regulatory framework. Intelligent distributed control plays a minor role in practice so far, although autonomous control systems have been developed in the last decade [2]. Recently the research on decentralized approaches based on multi-agent systems has been intensified and new flexible solutions have been proposed [3-5]. This paper gives an overview about decision making in power systems operation as of today, investigates the applicability of self-organizing systems, and outlines an exemplary application from current research in decentralized power flow control.

2 Self-Organizing Systems in Power Systems Operation

In this section, an overview of challenges as well as important physical characteristics of power systems is given followed by a discussion of decision making in system operation and the applicability of self-organizing systems in real-time control.

2.1 Challenges of Power Systems Operation

Reliability and security of power supply are closely linked to maintaining three kinds of system stability [6]:

- Frequency stability: supply and demand of active power need to be balanced, otherwise frequency exceeds acceptable limits and loads or generators need to be shedded.
- Rotor angle stability: all synchronous generators in power plants need to maintain synchronism of their rotors, otherwise the generators are disconnected from the system which leads to a sudden loss of feed-in and thus frequency instability.
- Voltage stability: local demand of reactive power needs to be met, otherwise voltage can drop irreversibly. Supply of reactive power is typically provided by neighboring synchronous generators or special reactive power compensation equipment.

If one of these conditions is violated system-wide black-outs can occur. A major challenge is to fulfill these conditions at any time even though the system changes dynamically. In particular, contingencies have to be taken into account, e.g., the outage of a major transmission line. For this reason, TSOs operate the system in accordance with the N-1 criterion that requires an operational state in which any single piece of equipment can fail without yielding in an inacceptable post-contingency state (N representing the total number of pieces of equipment in operation). In this context, it has to be taken notice of protection devices that protect equipment from overload by disconnecting it from the system. Therefore, a failure that leads to an overload of equipment can cause cascading disconnection of further equipment and thus loss of stability. The prevention of such a cascade is one aim of the N-1 criterion and overloads can only be accepted for a certain time period ranging from milliseconds to some minutes depending on the type of equipment and severity of overload.

Since rotor angle stability is so far of minor importance in the meshed European transmission network, the focus will be set on contributions to frequency stability, voltage stability and prevention of overloads by power flow control in the following parts.

2.2 Modeling of Power Systems

In the following an approach to power system analysis typical in electrical engineering is presented to give a basic overview of important physical linkages and elements relevant for application of self-organizing systems.

Power systems can be modeled as a network of branches and nodes. Nodes represent sinks or sources of active power *P* and reactive power *Q* (for sustaining electromagnetic fields) as a net value of generator feed-in and load consumption at each node. Branches represent the network topology consisting of transmission lines and additional equipment such as transformers or controllable devices designed to influence the parameters of the topology. Each branch element connected between node *i* and *j* can be represented by three complex admittances $\overline{Y}_{i,0}$, $\overline{Y}_{j,0}$ and $\overline{Y}_{i,j}$ derived from its equivalent circuit diagram (shown in Figure 1 with voltages $\overline{V}$ and currents $\overline{I}$).

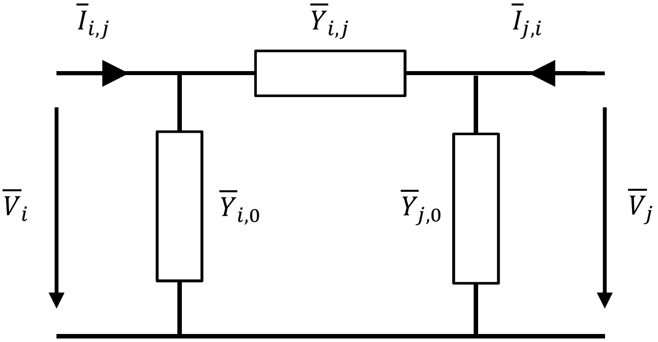

Fig. 1. Equivalent circuit diagram for branch elements (single-phase)

The branch elements need to be protected from overload which is typically regarded as a maximum of the current $\overline{I}_{el}$ flowing through the element. Given *P* and *Q* at each node *n* as well as the network topology, the resulting complex voltage $\overline{V}$ at the nodes as well as the complex currents $\overline{I}$ can be derived from equations (1-2) [7].

$$P_n + jQ_n = \overline{V}_n \sum_m \overline{y}^*_{nm} \overline{V}^*_m \tag{1}$$

$$\overline{I}_{el-i,j} = \left(\overline{V}_i - \overline{V}_j\right)\overline{Y}_{el-i,j} + \overline{V}_i \overline{Y}_{el-i,0} \tag{2}$$

Here, $\overline{y}_{nm}$ is the element from the *n*-th row and the *m*-th column of the node admittance matrix which comprises the admittances of all branch elements and their topological interconnection. For details on the formation rules of this matrix see [6-7].

In addition, the following physical linkages should be taken into account:

- The voltage magnitude V is closely linked to the local availability of reactive power Q. Reactive power can also be transported between nodes but its flow causes a higher loading of the corresponding transmission lines as well as active power losses. Also the flow of power through any kind of conducting equipment requires reactive power.
- The voltage angle φ between two nodes is closely linked to the active power flow P between the nodes.
- Deviations from the nominal frequency f_n (in Europe 50 Hz) evolve when supply of active power differs from the active power consumption by loads.

2.3 Decision Making and Control Actions in Real-Time Operation

Considerations of applying self-organization to power systems operation require knowledge about the decision making and potential actions in the system. In the following typical means of influence in power systems operation are summarized.

For generators the values of its active power feed-in P_{gen} as well as the reactive power supply Q_{gen} can be controlled. The base active power feed-in $P_{\mathrm{gen,base}}$ is set by the power plant operator and follows a schedule derived from supply obligations mainly generated at the electricity market. It is constant for a certain supply period (e.g., 15 min). If the market clearing results in transmission system overloads the TSO can enforce a (mostly costly) change of generation schedules referred to as redispatch. In addition, the active power can temporarily differ from $P_{\mathrm{gen,base}}$ by a value $P_{\mathrm{gen,r}}$ for ancillary system services to ensure frequency stability by balancing system-wide supply and demand at any point of time (known as primary, secondary and tertiary reserve, see [8]). The value of $P_{\mathrm{gen,r}}$ depends on control parameters defining how a generating unit contributes to mediating frequency deviations - e.g., due to noise and forecasting errors of load and renewable energy feed-in - and can be controlled on demand of the corresponding TSO (the contribution of a generator can, e.g., result from special control reserve markets). Additionally, the set point of the node voltage V_{gen} or – due to the strong coupling of voltage magnitude and reactive power – almost equivalently reactive power Q_{gen} can be set on demand of the TSO in order to achieve a desired voltage profile throughout the system and to optimize reactive power flows.

Loads are typically considered as demands of active power P_{load} and reactive power Q_{load} which cannot be controlled during normal operation and which can only be shedded in an emergency case. However, recent developments (e.g., in the fields of demand side management and smart grids) could change these conventional assumptions and could offer a superposing value of $P_{\mathrm{load,r}}$ and $Q_{\mathrm{load,r}}$ controllable in a certain range to a base load of $P_{\mathrm{load,base}}$ and $Q_{\mathrm{load,base}}$ [9]. Active and reactive power consumption are tightly linked and control of either value results in an approximately proportional change of the corresponding value. As the electricity service demanded by consumers usually regards active power, the typical control parameter is $P_{\mathrm{load,r}}$.

Transmission lines themselves are uncontrollable and the only action available is to disconnect them from the system (e.g., in case of overload or failure). Nevertheless, the admittances being part of equations (1-2) can be influenced by the use of special equipment such as controllable transformers, compensations, HVDC (High-Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) devices being under control of the TSO. These can be classified as series controlled, shunt controlled and combined shunt and series controlled devices. Series controlled devices are installed in series with a transmission line and their admittance influences voltage magnitude and angle resulting in control over voltage drop over the line and power flows. Its control value $ctrl_{\text{series}}$ changes the admittance $\bar{Y}_{i,j}$. Shunt controlled devices are installed line to ground, thus giving control over $\bar{Y}_{j,0}$ and $\bar{Y}_{i,0}$. Their control values $ctrl_{\text{shunt}}$ mainly influences reactive power and reactive power flows. Combined controlled devices influence all aforesaid element admittances by their control value $ctrl_{\text{combined}}$ and thereby combine the effects of shunt and series devices. For details on types and modeling of controllable devices see [10], Figure 2 gives an overview over relevant devices in practice and under development.

Additionally, every element of the topology as well as every generator and load can be disconnected from the system by triggering a breaker. This can be described as changing a binary control value $break_{\text{el}}$ from *on* to *off*. As mentioned, a typical case is the protection against overloads or load shedding in order to ensure frequency or voltage stability. Disconnection is either undertaken automatically or it can be initiated by the TSO. For loads and generators, a disconnection means a sudden change in P and Q at a node. Disconnection of topological network elements results in a sudden change of the admittances in equations (1-2). A similar effect has the change of interconnection of lines with couplers at certain nodes in the system (with a control value $couple_{\text{bus}}$).

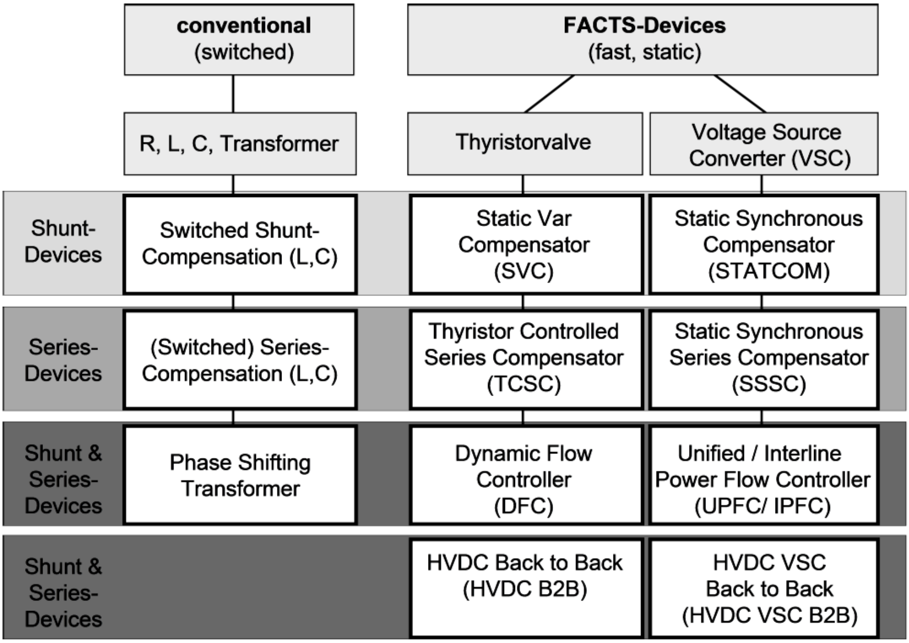

Fig. 2. Overview of controllable network devices (Source: [10])

Furthermore, from equations (1-2) it can be obtained that - at least to some extent - all state variables are interdependent and thus have impact on all examined fields of interest. However, the influence of different control values varies significantly and can be neglected depending on the application. Table 1 summarizes dynamically changing values in the system and shows qualitatively their influence on frequency stability, voltage stability and overload prevention. The table can serve to determine the decisive control values for new applications of power system control, nevertheless, a detailed system analysis including all control values should be undertaken to determine their influence in the specific scenario and whether or not they can be neglected.

Table 1. Dynamic values in power systems, entity in charge, and influence on stability and overloads (qualitative range: +++/++/+/0)

Dynamic value	Control sphere	Influence on frequency stability	Influence on voltage stability	Influence on overload prevention	Comment
$P_{\text{gen,base}}$	Market (TSO)	+++	0	+++	Possibly redispatch by TSO
$P_{\text{gen,r}}$	TSO	+++	0	+	Ancillary service purchased by TSO
Q_{gen}	TSO	0	+++	+	
$P_{\text{load,base}}$	Market	+++	Indirectly (by $Q_{\text{load,base}}$)	+++	Consumer behavior, possibly price-dependent
$Q_{\text{load,base}}$	-	0	+++	+	Follows mainly $P_{\text{load,base}}$
$P_{\text{load,r}}$	- (Future: TSO)	+++	Indirectly (by $Q_{\text{load,r}}$)	+	(Future: Ancillary service purchased by TSO)
$Q_{\text{load,r}}$	-	0	+++	+	Follows mainly $P_{\text{load,r}}$
$ctrl_{\text{series}}$	TSO	0	+	++	
$ctrl_{\text{shunt}}$	TSO	0	+++	+	
$ctrl_{\text{combined}}$	TSO	0	+++	++	
$break_{\text{el}}$	TSO	0	+++	+++	
$couple_{\text{bus}}$	TSO	0	+	+	

As another aspect for designing innovative and applicable control systems, the critical time for reactions, the control ranges and times for response of controllable devices, and the extent of coordination needed have to be taken into account. Table 2 gives a brief overview regarding these concerns.

Table 2. Coordination extent, critical times for reaction, and response times of devices for frequency stability, voltage stability and overload prevention

	Coordination	Critical time for reaction	Response time of devices
Frequency stability	System-wide	some 100 ms (major disturbance, keep frequency in boundaries) to some min (adjust frequency)	some 100 ms (local controller with limited range for ancillary services, load shedding) to some min (base feed-in)
Voltage stability	Local	some s (major disturbance) to several min	some ms (fast FACTS, HVDC) to some s or min (conventional controllable network devices, reactive power supply by generators)
Overload prevention	Region	100 ms (short circuit) to some min (moderate overload)	some ms (fast FACTS, HVDC, breaker) to some s or min (conventional controllable network devices)

2.4 Applicability of Self-Organizing Systems

Based on the characteristics of power systems control presented above, the applicability of self-organizing systems in this matter is discussed. In the following, self-organizing systems are understood as software processes being adaptive to changes in environment, capable of coordination and own decisions making without the need of a central hierarchic instance. A significant potential is seen in the capability of such decentralized systems to adapt in real-time compared to centralized decision making as of today that can take up to several minutes. This long time makes it necessary to operate the system in a possibly inefficient state because any contingencies need to be addressed upfront without accounting for the adaptiveness of the system. A first methodology for the economic assessment of such real-time control capabilities has been developed in [11] and indicates significant economic benefit. In addition, real-time adaptiveness can contribute decisively maintaining reliability and security of operation in an N-1 case.

Some insights for the targeted design of decentralized control systems that can be gained from Tables 1 and 2 are:

1. Not all relevant control values are in the sphere of influence of the same entity in the current regulatory framework, thus either the values not under control of the TSO are taken as external inputs in control systems or the framework needs to be changed.
2. Control values for frequency stability, voltage stability and power flow control are often interdependent, thus either all fields of interest are considered at the same time in a self-organizing system, or it must be assumed or verified that other fields are not critically influenced.
3. Time ranges of critical time for reaction as well as for the control capabilities of the devices vary widely. A detailed analysis must be undertaken specifying the

objective and constraints of application of the control system under consideration of the speed of the controllable devices as well as potentially occurring actions by other decision making processes in the meantime (e.g., a fast controlling FACTS device could react to a short circuit in time, whereas a conventional device could not serve for this purpose but is still sufficient to react in case of moderate overloading).

Taking these insights in mind, it can be distinguished between two general concepts for self-organizing systems:

- *Comprehensive Self-Organizational Approach*: all control values are controllable and emerge from self-organization.
- *Functional Self-Organizational Approach*: a specific problem is addressed by a self-organizing system complementing partially centralized or locally controlled systems.

The comprehensive self-organizational approach involves all system elements and needs to address both kinds of stability as well as overload prevention. This approach is of highest complexity but enables to gain the full benefit of self-organizing systems. However, this approach requires a change of the framework of European power systems as the existing market structure would have to be renewed. Such a bottom-up approach based on multi-agent-systems has been published in [12] and is still under development. As of today, this approach only makes use of control actions regarding active and reactive power supply and demand, but the system architecture generally offers the flexibility required to extend it in order to include topological actions as well.

The functional self-organizing approach has the advantage to be more easily applicable to an existing framework. Depending on the challenges to meet and the actions available, it can be identified how available controllable equipment could contribute. It must be assured that control actions do not cause violation of other operational requirements, thus (ii.) and (iii.) discussed above need to be specifically addressed. In the following, the applicability of functional approaches to the fields of interest in this paper is discussed.

Self-Organizing Systems for Frequency Stability

In order to ensure frequency stability in case of major disruptions (e.g., outage of a power plant), a fast and extensive response in the time range of some 100 ms by $P_{\mathrm{gen,r}}$ and $P_{\mathrm{load,r}}$ needs to be achieved in a coordinated process of power generation units and loads throughout the system. To apply self-organizing systems to this problem is challenging as a huge amount of communication over a wide-spanned area is needed. However, in a functional approach, this first reaction could be undertaken by local control systems (as of today by proportional and integral controllers) responding immediately to frequency deviations in order to avoid exceeding acceptable boundaries (e.g., 49 Hz) and the latter process of adjusting frequency to f_n as well as the transition to an improved configuration of $P_{gen,r}$ and $P_{load,r}$ could be organized decentralized (e.g., by application of self-organization in tertiary control).

Self-Organizing Systems for Voltage Stability

Voltage stability is of a rather local character and of a less critical time range, thus communication and coordination processes could be more easily executed in time than in the application for frequency stability. In addition, the most decisive control values with the exception of Q_{load} can be controlled by the TSO. Therefore, voltage stability constitutes a promising field for the application of self-organizing systems.

Self-Organizing Systems for Overload Prevention

Power flows are only partially in control of the TSO as they primarily derive from active power supply and demand configuration ($P_{gen,base}$, $P_{load,base}$). Nonetheless, controllable devices (particularly $ctrl_{combined}$, $ctrl_{series}$) offer influence in a limited range. As in the case of frequency stability, some applications (e.g., reaction to a short-circuit on the line) require a short response time of 100 ms. In the case power flow control, this time could be met more easily, as coordination is only needed regionally, nevertheless, achieving the response in time including communication and decision making is still challenging. Therefore, a functional approach for improved reconfiguration of control values as a complement to short-term local control or protection could be of high potential. An example for this application is presented in the next section.

3 Self-Organization in Coordinated Power Flow Control

In the following, a decentralized power flow control system as an example for applications of functional self-organizing approaches from recent research is presented [13-15]. First, the need of coordination of controllable devices in power flow control and the current practice of centralized coordination are outlined. Then, the agent-based decentralized approach is explained and investigated in detail.

3.1 Need for Coordination in Power Flow Control

In meshed transmission networks in a current framework with externally defined generation and load configuration, power flows can mainly be influenced by series or combined controlled devices such as Phase Shifting Transformers (PSTs) as well as certain FACTS and HVDC devices (see section 2.3). These devices are referred to as Power Flow Controllers (PFCs) in the following. Each PFC has a significant influence only in a certain neighborhood. Dimension and shape of this neighborhood depend on the type of device and the surrounding network. This influence can be determined by a sensitivity analysis using power flow analysis methods [6]. Figure 3 shows an example of a grid with several PFCs.

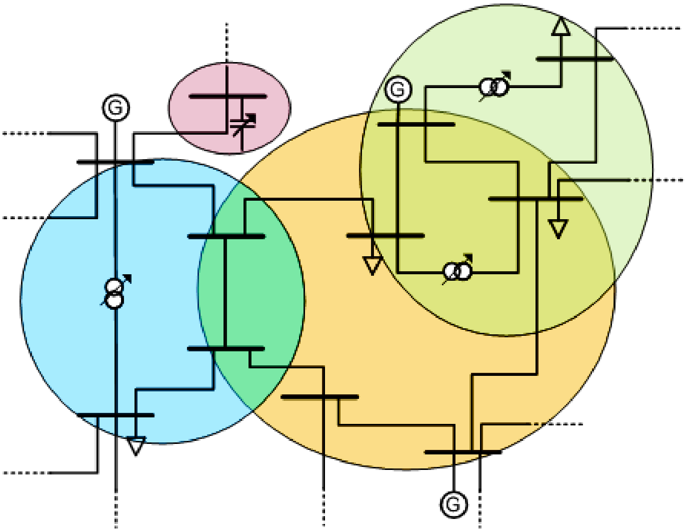

Fig. 3. Transmission network with generators (G), loads (△), and controllable network devices (marked with →)

The simplest way to implement a control system for PFCs is the use of a local control for each device. Local control means that one or several PFCs only address the control of the transmission lines within a certain region (which could be the control area of a TSO) while the neighborhood of influence of these PFCs could cover additional uncontrolled transmission lines from a control area of another TSO. Input values of local control are measurements of transmission line power flows. Further interaction with other controlling devices is not foreseen for local control. If several PFCs with mutual influence are integrated into the transmission system, the combination of several local controls might not always provide the optimal operation of the overall transmission system. A coordinated control system can provide several operational benefits which cannot be achieved by local control:

- Uncoordinated operation of PFCs may cause overcompensation of transmission lines within their neighborhood of mutual influence.
- When PFCs located in several control areas have mutual influence, counterproductive control actions may happen.
- In case of changing network topology (e.g., caused by a major line outage) local control of PFCs will not be able to adapt to the new network topology.

In general, the installation of multiple PFCs with mutual influence requires sophisticated coordination mechanisms in order to increase the overall transmission capacity and to avoid conflicts that may lead to unexpected behavior.

3.2 Current Practice: Central Coordination

Each day after finalization of the market bidding procedures each TSO analyses the day-ahead system security for its own transmission network. This analysis includes an

N-1 security analysis with an estimation of the PST settings in order to determine if there are congestions to be solved, e.g., by topology or redispatch measures. The estimation of PST settings only considers local control of the devices. During real-time operation the TSOs have to deal with forecast errors of the day-ahead security planning. Hence, the settings for the PSTs have to be determined based on real measurements coming from the transmission system. However, since currently there is no general wide-area monitoring system (WAMS) implemented in Europe, each TSO monitors its own grid, including a few transmission devices of the neighbouring TSOs. This information is the basis for the determination of PST settings. If PSTs have influence on the power flow of neighbouring TSOs (e.g., in the Benelux region), then changes of the tap positions have to be agreed with all involved TSOs. This coordination is carried out by telephone conversations between the control centres. Usually the time for agreeing about a tap change operation can last up to 15 min. A first step towards more efficient real-time coordination between the TSOs is made by the establishment of joint security centres. The participating TSOs submit their current system measurements as snapshots to the security centre, which then merges the individual data to a complete dataset which is basis for security analysis. As an example, the Coordination of Electricity System Operators (CORESO) provides such a quasi real-time analysis of the overall transmission system of the participating TSOs since July 2009. By performing a permanent monitoring of the transmission grid, updated through periodical snapshot, a security analysis is provided every 15 min.

However, all real-time control features which are planned for installation are until today based on a centralized data collection, which cannot provide coordination of PFC with a higher frequency than every 15 min. For responding to contingencies during unforeseen emergency situations this frequency is too small to protect the system against cascading events. Optimization tools are not applied for the coordination of PFC set-points, among others because they are yet too time consuming. Instead the coordination is performed by telephone conversations and based on expert knowledge supported by security calculations.

3.3 New Approach: Agent-Based Decentralized Coordination

This sub-section presents a new approach (still under development) for a coordinated control system. In contrast to existing coordination methods, this multi-agent based coordinated control system does not have any hierarchical structures. All communication and decisions are taken directly on the device level. This structure allows fulfilling the following requirements:

- To reduce the amount of data to be exchanged between neighboring control areas.
- System topology changes are detected automatically to be able to adapt the control immediately after the occurrence of contingencies
- The control system is robust in case of system disturbances. In particular during cascaded events (N-2 situations or higher) the coordinated control stabilizes the system with corrective control actions.

Description

The control variables are the set-points of PFC devices. The controlled variables are the power flows on transmission lines. Disturbances to be compensated by the coordinated control are caused by changes in load and generation or by tripping of transmission system devices (e.g., caused by a fault).

For the implementation of a multi-agent based coordinated control system with respect to the conditions described above an adequate communication network is needed. For this purpose each serial device of the power system (transmission line, transformer and PFC) is represented by a software agent. There are two kinds of agents, controlling (active) agents and non-controlling (passive) agents. Each PFC is equipped with a controlling agent. Each non-controllable electrical device within the area of influence of PFCs is equipped with a non-controlling agent (e.g., equipped with a Phasor Measurement Unit (PMU)).

The non-controlling agents permanently submit messages about local state information to their neighboring agents. These agents update the messages with local data and forward them to the next neighboring agents. In this way the messages are submitted along the power system topology until a stop criterion is reached. Controlling agents installed at each PFC receive these messages to gather information about the current system topology, the sensitivity for control actions on network devices and the demand for such actions. An example for this procedure is explained below, based on the network situation presented in Figure 4.

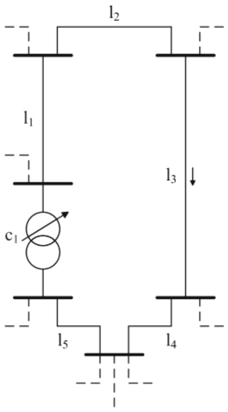

Fig. 4. Exemplary network situation

The agent of transmission line l_3 submits one message to every agent of its neighboring devices. These messages contain information about the impedance of transmission line l_3 and the identifier of the sending end-node from which the message was submitted. All agents of the devices physically connected to the sending end-node receive the message and add the impedance of their own transmission line. The accumulated impedance of one message expresses the transmission path impedance. Subsequently the messages are updated and forwarded along the topology. Finally the controlling agent of PFC c_1 receives one message from line l_3 at each end-node of the PFC. The first message was submitted along the transmission lines l_3, l_2 and l_1, while the second message was transmitted along the transmission lines l_3, l_4 and l_5. By analyzing these two messages the controlling agent concludes that the transmission line l_3 is located on a transmission path connecting the two end-nodes of the PFC and determines the total impedance of this transmission path by summing up the accumulated impedances stored in the two messages.

Each controlling agent evaluates this information by use of certain functions in order to determine the appropriate control actions. In this evaluation control requests of all transmission lines in the sphere of influence of a PFC are compared concerning severity of the request and the expected influence of the PFC for controlling the power flow on this device. Simulation results have shown that the multi-agent control reacts correctly and efficiently on detected overloading of transmission system devices in due time before cascading faults occur. The fact that the agents can exert efficient coordinated control without knowledge about the global system topology shows the immense potential for scalability and fault-tolerance of this distributed coordination of PFCs. Figure 5 visualizes the procedures of the control system.

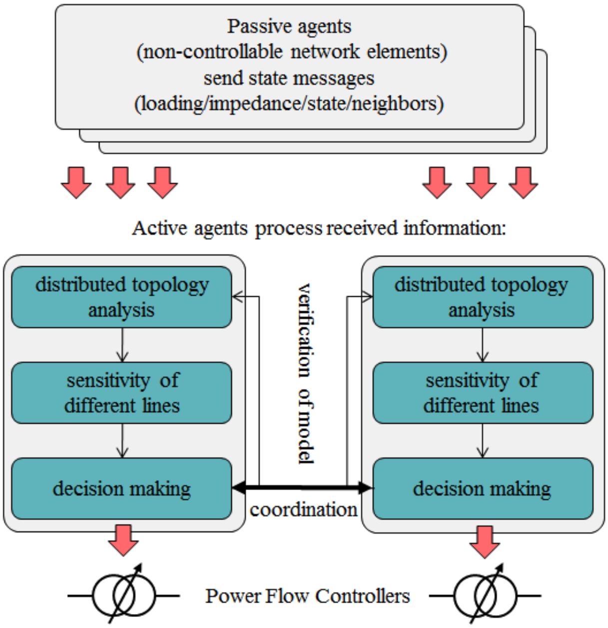

Fig. 5. Schema of a multi-agent-system for decentralized power flow control

Discussion

This coordination method allows for the coordination of series connected FACTS devices and PSTs. Up to now the implementation includes devices with discrete control steps which have a linear characteristic. The implementation of further types of PFCs including HVDC links is possible.

This coordination method adapts the control of PFCs when contingencies occur. This means that the set point of PFC devices can be modified timely in post-disturbance situations. Such corrective actions allow the TSO to operate the system without satisfying the strict N-1 security criterion. Since system topology changes are detected fully automatically without any necessity of communication with the control center, this approach is also robust in contingency situations of any grade.

This coordination method does not require any global data of the transmission system. The agents only submit information which is necessary for the coordination. The multi-agent system is supposed to be installed across the borders of system operators. However, the agents of neighboring system operators will only receive data from the neighboring networks which is required for the coordination (only from the area where the PFC has influence).

Field of Application and Requirements for the Implementation

The field of application of the multi-agent approach is real-time coordination. The method can be applied to perform an adequately fast automatic response to system events. This also includes severe system disturbances.

To achieve the benefits of this coordination method concerning fast reaction in contingency situations, fast PFC devices (of the FACTS family) have to be applied.

Since this approach is fully distributed significant modifications to the control centers are not required. However, the N-1 security constraints have to be adapted in the day ahead planning process and for the operation in the control centers. This softening of the N-1 criterion is required in order to achieve an increase of transmission capacity as response to the increased flexibility gained by using FACTS devices.

The majority of the modifications have to be made on the substations level. Agents have to be installed for each transmission line and for each PFC within the area to be coordinated. Each non-controlling agent must be connected to measurement devices which observe the loading and the status of the corresponding transmission line. Each controlling agent must be connected to a PFC controller to transmit the control signals. Between neighboring agents there must be appropriate communication channels.

4 Outlook

The application of self-organizing systems in power systems control promises significant potential to contribute to a reliable, secure and efficient network operation by enabling real-time adaptivity in contrast to current practices of centralized decision making. The capabilities of self-organizing systems particularly meet the challenges of ensuring voltage stability and preventing overloads. Therefore, research and development in these functional approaches should be continued with a close consideration of time constraints and interdependencies with other critical measures of system operation. Furthermore, the extension of recent comprehensive bottom-up approaches by inclusion of topological actions would be eligible. For power flow controllers, a decentralized coordination system based on agents has been developed. Benefits include increase of operational security by increased real-time adaptiveness in N-2 cases as well as improvement of operational efficiency by enabling corrective real-time measures, thereby possibly allowing for relaxation of strict N-1 security planning.

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